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Dual-rod Yb:YAG laser for high-power and high-brightness applications

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Abstract

We describe a diode-pumped Yb:YAG laser producing 1080 W cw with 27.5% optical-optical efficiency and 532 W Q-switched with $M^2=2.2$ and 17% optical-optical efficiency. The laser uses two composite Yb:YAG rods separated by a 90 degree quartz rotator for bifocusing compensation. A microlensed diode array end-pumps each rod using a hollow lens duct for pump delivery. By changing resonator parameters, we can adjust the fundamental mode size and the output beam quality. Using a flattened gaussian intensity profile to calculate the modefill efficiency and clipping losses, we compare experimental data to modeled output power vs beam quality.

High-average-power laser operation with good beam quality has long been an active area of development. Power oscillators offer greater simplicity compared to master-oscillator power-amplifier (MOPA) systems, but the finite TEM₀₀ mode size possible¹ limits power scaling or results in multimode operation with lower beam quality. Considerable effort has been devoted to studying laser resonators to achieve high power and brightness.^{2,3}

A promising method to improve power scaling and reduce thermal effects is to minimize heat generation by the use of Yb³⁺ doped materials.^{4,5} Although Yb³⁺ offers lower heating rates compared to Nd³⁺, the quasi-three level nature of the laser transition requires careful engineering to achieve high power and efficiency.^{6,7,8} One of the challenges of designing a Yb³⁺ system is delivering pump light of sufficient intensity. In the diode-array end-pumped system described here, pump intensities >50 kW/cm² enable efficient laser operation far above threshold. Correspondingly, high-average-power operation is achieved with a relatively small cross-section laser rod. This enables the laser rod to be the mode-limiting aperture in order to obtain good beam quality with high efficiency.

Recently, very high brightness operation has been demonstrated from Nd:YAG laser oscillators incorporating a symmetric cavity with two identically pumped laser rods separated by a 90 degree quartz rotator for bifocusing compensation.⁹ Here, we describe a similar resonator using two Yb:YAG laser rods. Diode-array end-pumping is used with a hollow lens duct for pump delivery,¹⁰ with the laser beam passing through each hollow lens duct and the two halves of the diode array.

The composite laser rods have a $1 \times 10^{20} \text{ cm}^{-3}$ Yb-doped section, nominally 2 mm in diameter by 50 mm long, and flanged, undoped end caps. For this system, the laser rod diameter tapers along the length for parasitic suppression.¹¹ The diode arrays are made up of microlensed diode bars 1.5 cm long, mounted on silicon microchannel heatsink packages.¹² Each diode array contains 38 packages, resulting in > 4.56 kW total pump power. The diodes were operated with a cooling water temperature of 30 C to obtain the desired pump wavelength. The cooling water temperature of the laser rods

was varied between 0 and 20 C. The resonator is symmetric, with the two laser rods separated by the 90 degree quartz rotator and a negative lens to partially compensate thermal lensing in the laser rods. The high reflector and the 20% reflectivity output coupler are both 50 cm radius of curvature. The length of the resonator was varied from 84 to 116 cm to achieve a given mode size in the laser rods. Figure 1 shows a schematic drawing and photograph of the system.

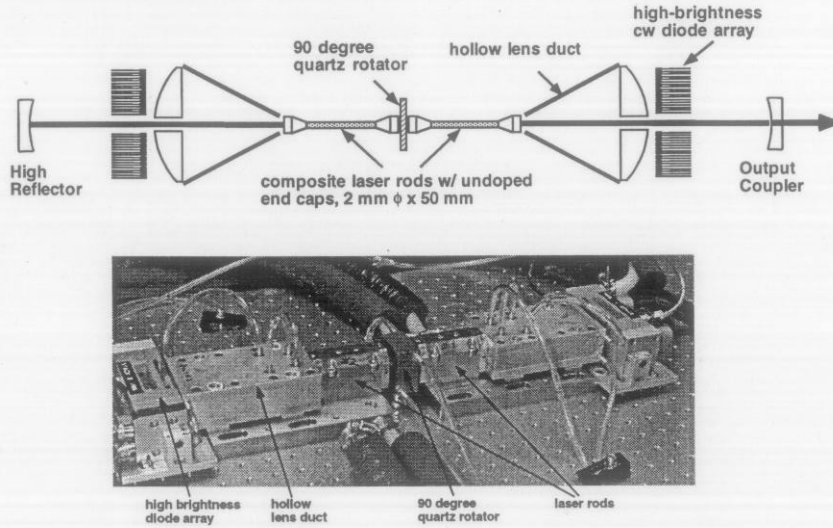


Fig. 1. Schematic diagram and photograph of our dual rod Yb:YAG laser with birefringence and bifocusing compensation

Figure 2 shows a plot of output power vs pump power in multimode operation. The maximum output power achieved is 1080 W at a total diode pump power of 3930 W, yielding an optical-optical efficiency of 27.5%. The electrical power supplied to the diodes is 8780 W, corresponding to an electrical-optical efficiency of 12.3%. At this operating point the diodes are only operating at 35 W/cm, below their maximum efficiency and power rating of 40-50 W/cm. The resonator length is 84 cm, yielding a beam quality of $M^2 = 13.5$ measured at 1080 W output.

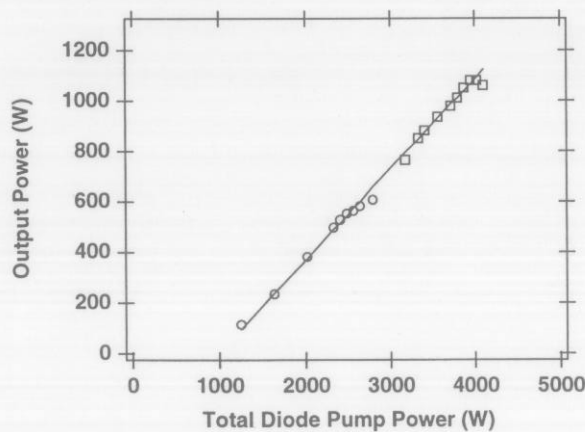


Fig. 2. Output power vs total diode pump power for a resonator configuration yielding $M^2 \approx 13.5$.

Since the variable thermal lens of the laser rods limits the range of operation for a given resonator configuration, the data in Fig. 2 is shown for two different resonator configurations. The data shown below 3000W pump power (circles) corresponds to the laser system with only the 90 degree quartz rotator between the two laser rods. At approximately 2800 W pump power, the output is beginning to roll off as the resonator approaches the stability limit. For the data above 3000 W pump power (squares), a -15 cm compensating lens was used. Also shown in Figure 2 is the predicted output power vs pump power based on a quasi-three level laser energetics model using a flattened-Gaussian beam profile described below.¹³

Using a commercial software package¹⁴ to calculate the TEM₀₀ beam waist, ω_{00} , at the center of each rod, we plot the measured beam quality for a number of resonator configurations in Fig. 3. Thermal lensing in the rods was modeled assuming uniform heating due to the difference between the absorbed pump and laser wavelengths. To achieve resonator stability at a given pump power, negative focal length compensating lenses were used between the two laser rods. To first order, the additional lens only changes the range of pump power over which the resonator is stable without changing the TEM₀₀ beam waist, ω_{00} , or the beam quality. The fastest lens used was -5 cm, enabling a pump power of up to 3114 W at $M^2=2.2$ from a resonator length of 116 cm. The beam quality was calculated using measurements of the second moment of the intensity distribution taken from camera images at various distances from a focusing lens.¹⁵ Along with the experimental data, Figure 2 shows the predicted beam quality assuming the multimode beam size, $W=M*\omega_{00}$, remains constant and is equal to 0.9 mm.

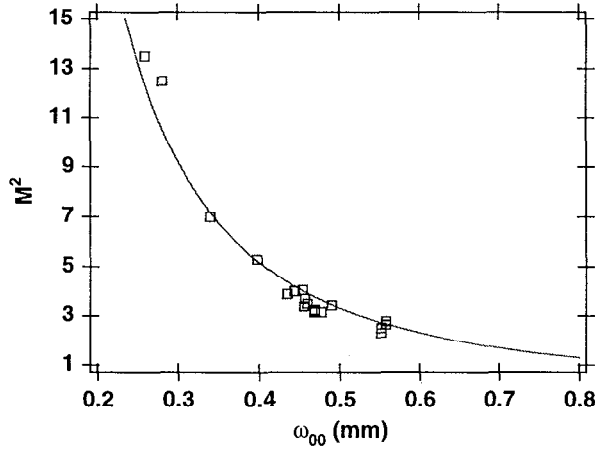


Fig. 3. Measured beam quality (M^2) vs calculated TEM₀₀ beam waist, ω_{00} in the center of each laser rod. The line through the points is a prediction of beam quality, assuming the multimode beam size $W=M*\omega_{00}$ is equal to 0.9 mm.

We performed high repetition rate Q-switching experiments by inserting two acousto-optic Q-switches in the resonator. At a measured beam quality of $M^2 = 2.2$, we obtained 532 W output Q-switched at 10 kHz, with 3114 W of pump power (17% optical-optical efficiency). The pulsewidth was 77 ns FWHM.

To model laser energetics, we use a quasi-three level laser energetics model.¹³ We had previously used an embedded gaussian formalism to calculate modefill and cavity transmission, which are parameters in the energetics model, for large fundamental mode and low M^2 beams.¹⁰ In order to improve the description of the intracavity beam, particularly for multimode operation, here we describe the beam as a flattened gaussian arising from the superposition of the Hermite-Gaussian modes supported by the resonator. We use the analytical expression for the modal decomposition of a flattened gaussian profile as described by Borghi and Santarsiero¹⁶ to calculate modefill and clipping loss for a flattened gaussian beam of given beam quality and mode size.

A brief outline of the procedure follows. Starting with an M^2 value and a TEM_{00} beam waist, ω_{00} , the form of the flattened gaussian intensity profile is given by

$$I_N(r) = e^{-\left[(N+1)\left(\frac{r}{W_B}\right)^2\right]} \sum_{n=0}^N \frac{1}{n!} \left[(N+1) \left(\frac{r}{W_B}\right)^2 \right]^n$$

where $N = [(3/2)(M^2 - 1)]$ with the square brackets denoting round-off to the nearest integer and $W_B = \omega_{00} ((N+1)/2)^{1/2}$. Note that in terms of the multimode beam waist defined by the second moment of the intensity distribution W , $W_B = (1/M)((N+1)/2)^{1/2} W$. The modefill is then given by

$$\eta_{\text{modefill}} = \frac{1}{\pi r_0^2} \int_0^{r_0} I_N(r) 2\pi r dr$$

where r_0 is the radius of the laser rod. The 1-way cavity transmission due to clipping loss is taken to be

$$T_{1\text{-way}} = \frac{\int_0^{r_0} I_N(r) 2\pi r dr}{\int_0^{\infty} I_N(r) 2\pi r dr}$$

With modefill and clipping losses associated with beam quality, we can predict output power vs beam quality with our energetics model. Figure 4 shows a plot of cw and average Q-switched output power vs beam quality (M^2). Each beam quality corresponds to a different resonator configuration. The solid lines are the model predictions and the symbols denote data points from cw and 10 kHz Q-switched operation. For the upper curve, the data and calculation are for 3930 W of pump power. The lower calculated curve corresponds to 3114 W of pump power, while the data points are for pump powers of 3040-3175 W pump power. At this repetition rate, the model and experimental output powers are similar for cw and Q-switched operation. The oscillations in the model arise from the discreteness of the Hermite-Gaussian modes,

particularly at low values of M^2 . The model, which is in good agreement with the data, predicts only a slight rolloff in output power as the M^2 is reduced from 10 to 5, with further reductions in output power as M^2 goes below 3. The model also predicts that the $M^2=2.2$ result of 532 W at 3114 W of pump power would be scaled to 750-850 W with 3930 W of pump power.

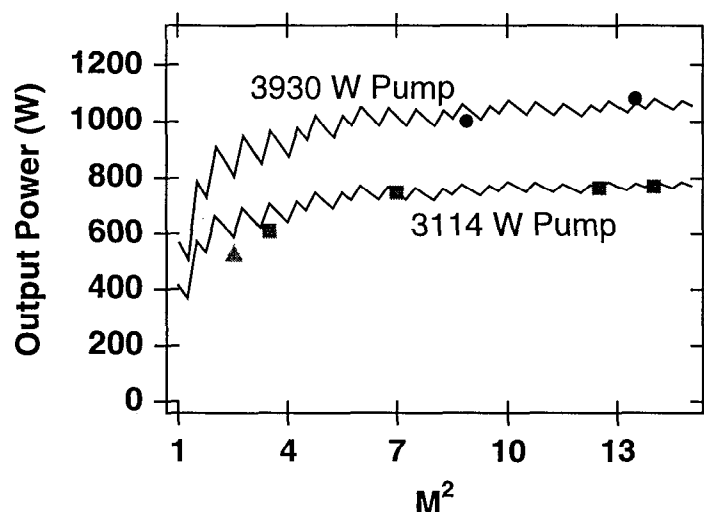


Fig. 4. CW and average Q-switched output power vs beam quality (obtained by adjusting the resonator length) for two different pump powers. The solid lines are the model predictions for 10 kHz Q-switched operation at 3930 W (upper curve) and 3114 W (lower curve) of pump power. Similar output power is found experimentally and theoretically for cw and high-repetition-rate Q-switched operation. The data points are for cw operation and 10 kHz Q-switched operation as follows: cw operation with 3930 W pump (circles), cw operation with 3040-3175 W pump (squares) and Q-switched operation at 10 kHz with 3114 W pump power (triangle).

To our knowledge, we describe here the highest power and brightness Yb^{3+} laser system reported to date. By varying resonator parameters, we demonstrate high average power laser operation over a wide range of beam quality. We find good agreement between experimental data and a flattened-gaussian quasi-three-level laser model to predict output power vs beam quality.

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